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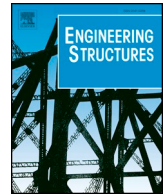
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Bridge safety is not for granted – A novel approach to bridge management

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ABSTRACT

Bridges are crucial points of connection in the transport system, underpinning economic vitality, social well-being and logistics of modern communities. Bridges have also strategic relevance, since they support access to emergency services (e.g. hospitals) and utilities (e.g. water supplies). Bridges are mostly exposed to natural hazards, in particular riverine bridges to flooding, and disruption could lead to widespread negative effects. Therefore, protecting bridges enhances the resilience of cities and communities.

Currently, most of the countries are not able to identify bridges at higher risk of failure, due to the unavailability of high-quality data, the mix ownership of the assets or the lack of a risk-based assessment. This paper introduces a risk-based approach to bridge management, alongside the gaps of current methodologies. Then, it presents a preliminary protocolled taxonomy for data collection of riverine bridges in flood-prone areas, while illustrating the implication of a national bridge inventory in the UK. This paper advocates the engagement of national authorities for developing a roadmap of policies leading to a unified bridge database functional for strategic risk assessment.

1. Introduction

Many towns and cities are located upon rivers. When a community grows, connection and accessibility become critical aspects of urban development, and rivers critical crossing points. Modern societies are extremely reliant on bridges, not only because they facilitate movements of people and goods, but also because they carry utilities over otherwise impassable obstacles.

River bridges are intrinsically highly exposed to flood-related hazards, more than any other infrastructural element. They are also vulnerable to man-made hazards, such as vessel [1] or vehicle collision [2]; however, these phenomena are out of the scope of this study. The high capital cost of bridges often results in few structures and limited redundancy in the system (i.e. no alternative crossing over the obstacle); thus, their failures can lead to cascading effects and disproportionately negative consequences for the community [3]. The economic consequences of a bridge failure include loss of utility, repairs and public overreaction costs [4]; the societal importance covers aspects of emergency management and post-disaster operations [5].

Recent events (Londonderry, 2017; Cumbria, 2009; Gloucestershire, 2009 and 2007; Boscastle, 2004) have underlined the need of placing resilience measures to mitigate the consequence of flooding on bridges and roads, in particular in the light of aging infrastructure and climate change. In the past two decades, progress has been made in the field of bridge engineering, especially in studying the damage mechanism of scour to bridges [6–14]. However, those are limited either to theoretical aspects or to case studies of single bridges, due to the lack of homogeneous detailed information and demanding computational processes.

A few studies have investigated the bridge vulnerability at larger scale, considering the systemic risk of a bridge as an element in the wide transport network (e.g. [15]).

Investigating bridge vulnerability at larger scale is currently challenging because a complete picture of the bridge stock does not exist, which causes loss of control over the assets. Nevertheless, effective bridge management is based on organised and complete data of the bridge stock, thus more research is needed in order to develop better practice.

This paper aims to set the scene for a holistic risk-based management system for bridges, based on a national bridge database. This study overviews current practice of bridge management, framing it within a risk-based approach. It also provides evidence for the need of a more systematic and protocolled data collection, proposing a new taxonomy for bridges at risk of flooding. Finally, it discusses the development of a national bridge inventory for the UK.

2. Motivation and background

It is estimated that the UK has more than 160,000 bridges [16] (Fig. 1). The annual expenditure on maintenance and repair of national bridges in England only is around £180 m (France €50 m, Norway €30 m, Spain €13 m), and the estimated maintenance backlog for local authorities bridges is £590 m [16]. Despite the high costs associated with bridges, the absence of a national bridge database makes these number quite unreliable [16].

In 2009, six bridges collapsed and 16 were closed to the traffic due to intense flooding in the Cumbria region (North-West of England); this

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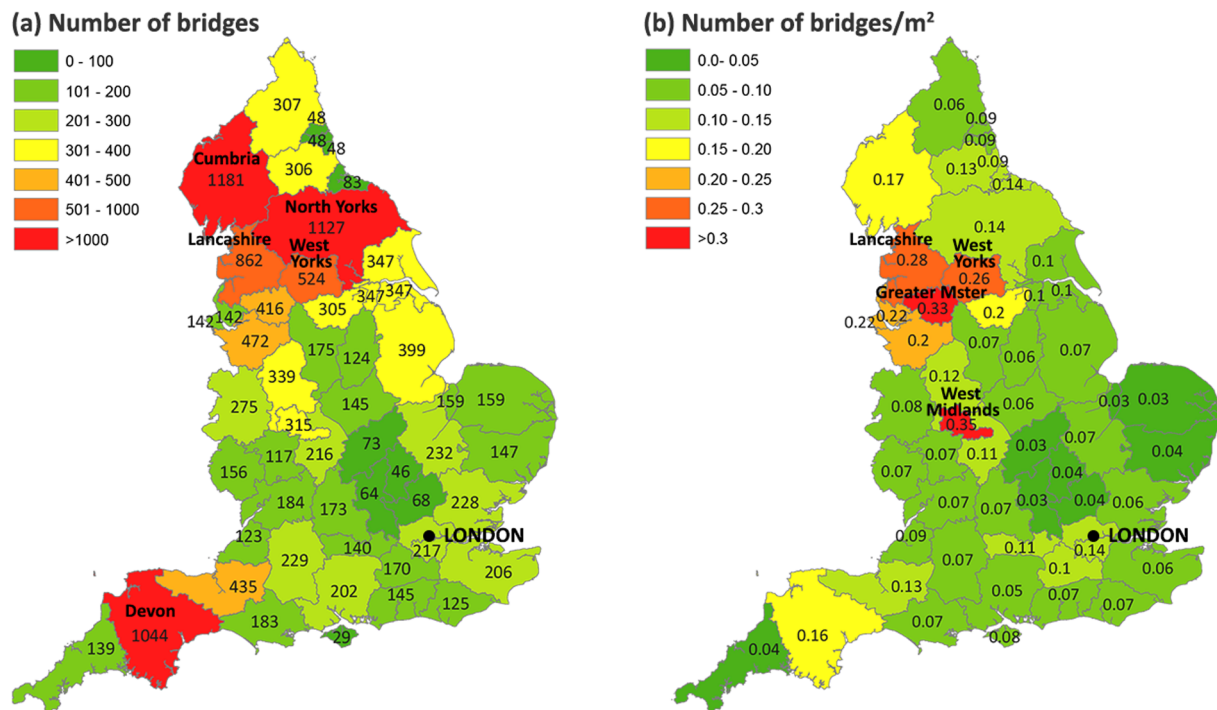


Fig. 1. The absolute number of bridges at county level (a), and the number of bridges in relation to the county area (b). Such data includes both rail and highways bridges in England; finer details are not available at national scale (source: OS data). Abbreviations: “Yorks” is Yorkshire; “Mster” is Manchester.

flooding event caused damages for £34 m to the county's bridges and roads, and the collapse of one bridge killed a police officer [17]. Bridge collapses happen due to both natural and human actions. Flooding represents the cause of almost half of bridge failures [18] for a range of factors: (i) scour at foundation; (ii) hydrodynamic loads and pressures on the deck, piers and/or foundations; (iii) overtopping; and (iv) debris accumulation [1,19,20]. Since different types of bridges are sensitive to different failure mechanisms, having deep knowledge of the bridge stock is the first step for an effective risk management of bridges.

Globally, the definition of a univocal system of parameters for unequivocally classifying structures is advocated for defining criticalities and interventions, especially in the light of limited budgets [21]. Currently, various countries are attempting to develop a national bridge database for improving asset management, like France [22], Italy [23], Vietnam [24], Thailand [25], Iran [26], Taiwan [27] and India [28].

In the USA, following a major bridge collapse (Silver Bridge, Ohio, 1967), the Federal-Aid Highway Act of 1968 required every member state to compile the National Bridge Inventory (NBI) with the specifications of any bridge longer than six meters and used for vehicular traffic. Currently, the NBI is a unified database used to analyse bridges and judge their conditions, for safety and management purposes [29]. A robust digital data protocol is used to automate the exchange of bridge information in the various activities of a bridge lifecycle [30]. Although designed to be extended to local bridges, the inventory is currently limited to federal highways bridges. The NBI is adopted for in-depth national analysis (such as the annual Infrastructure Report Card [31]), and research studies (e.g. Shen et al. [20], Padgett et al. [32]; nevertheless, these analyses are mostly structural and do not focus on the effects of external or environmental factors.

In the UK, despite planned maintenance and infrequent failures, bridges are deteriorating. The UK infrastructural system is one of the oldest of the world [33]. Around the 40% of the UK bridges are thought to be historical assets [4], not intentionally designed to carry modern vehicles and withstand severe horizontal loading due to high water levels (for example, structural elements not designed to modern standards). Climatic and socio-economic changes (e.g. demand increase, change of vehicle fleet) may have also exacerbated bridge conditions;

thus, some bridges could have reached the end of the expected life span [34].

UK bridges are owned and managed by various (national and local) agencies, who use in-house management systems with various level of sophistication. This distributed ownership leads to a “notorious lack of national data” [16], which prevents from drawing reliable estimations [16,35,36]. For example, most of the UK bridges have similar characteristics to the collapsed bridges in Cumbria [34]; however, there is currently no capability to identify and quantify them. The quality of records is also undermined by the outsourcing of contractors who create and maintain records, who do not have access to a consistent structure file for all assets [16]. This lack of knowledge of the bridge population is recognised as a major problem and a pressing issue for progressing informed decisions in the long-term [16,37].

The risk of an asset is usually described as a combination of exposure, hazard and vulnerability. Rating risk on the structural characteristics alone (from the exposure data) or inspections has been revealed insufficient; the absence of other factors (such as environmental parameters) could mislead evaluations about an asset [15,16,27]. For example, the Shuang-Yuan Bridge collapsed in 2009 in Taiwan due to severe floods, despite judged in good conditions [38]. Various bridge taxonomies can be found in the earthquake literature for the purpose of vulnerability assessment, accounting for the hazard intensity (e.g. PGA, Peak Ground Acceleration) [39]. Nevertheless, a similar classification does miss for bridges exposed to floods.

This paper firstly provides an overview over traditional bridge management systems, as opposed to more holistic risk-based approaches; in particular, a case study illustrates capabilities and limits of a local bridge dataset in the UK. Then, it proposes a new bridge taxonomy for bridges at risk of flooding, as a mean for harmonising current datasets, producing homogeneous data and supporting decision-making. Finally, it draws implications and challenges regarding the practical implementation of a national bridge inventory.

3. Bridge management systems (BMSs)

Bridge Management Systems (BMSs) are used to systematically



Fig. 2. The traditional modular structure of a Bridge Management System (BMS).

control the bridge stock, and ensure both safety and performance. BMSs are functional at a range of levels (executive, planning, administrative, maintenance) for: (i) collecting inventory data in a systematic and organised way; (ii) carrying out inspections and damage assessment; (iii) planning repair and maintenance schedule; (iv) allocating funds.

A BMS traditional structure includes four standard modules [35] (Fig. 2). The Inventory Module collects data regarding the bridge stock; the Inspection Module collects inspection data to classify the condition state; the Maintenance, Repair and Rehabilitation (MR&R) Module monitors short-term and long-term plans for intervention; finally, the Optimisation Module integrates the previous modules for budget-expenditure forecasts.

The inventory is considered the most important part of a BMS [26,35,40], and most BMSs are just limited to this module. This limitation prevents many countries from adopting BMSs to make decisions on the risk state; for example, Belgium, France, Germany and Ireland base their decisions on engineering judgement [41]. Nevertheless, the modular format of BMSs is flexible and could allow the introduction of additional modules according to the users' needs (e.g. the Experience Module of the Danish BMS DANBRO) [42].

Some BMSs are national (Pontis in the USA, Robert et al. [43]; DANBRO in Denmark [41,44]; J-BMS, Japan Miyamoto and Motoshita [45]), others focus on a single city (e.g. Moscow, Brodski et al. [46]). Comprehensive reviews of BMSs and national models are offered, among others, by Flaig and Lark [35], Pellegrino et al. [40,47] and Woodward et al. [41].

In the UK, a national BMS is missing. Highways England has developed a Structures Information Management System (SMIS) for their assets, containing basic inventory and inspection data. They have also published two Design Manuals for Roads and Bridges (DMRB) containing information about current standards, advice notes and other published documents relating to the design, assessment and operation of trunk roads (BA 59/94 for new design [48]; BD 97/12 for existing structures [49]). A new document is currently in preparation (due 2019) for updating both manuals. Despite local authorities refer to the DMRB for practice, a national database is seen as an essential requirement for given a common core format to information and for the long-term management of the bridge stock [16]. Further guidance on scour at bridges and other hydraulic structures is provided by the CIRIA Manual (C742) [13]. This manual addresses scour problems affecting both new and existing structures; however, its up-taking is judged practically difficult, especially by non-experts [50].

3.1. Bridge classification

The bridge engineering literature is more developed in the earthquake community and the concept of bridge taxonomy has been already advanced for risk assessment [39,51]. Available classifications include main typological features (such as the number of spans, design level, material, pier type, abutment type, superstructure type and continuity), and a measure of the hazard (PGA) [52–55]. Existing classifications vary due to the geographic location and objectives of the study, and often focus on individual bridges or the most common type in a region. Given this limitation, existing taxonomies may not be appropriate to fully describe different areas or bridge types [39,51].

The UK is not an earthquake-prone country; therefore, no classification is available in the seismic literature that refers to British bridges.

Different types of classification underpin the Highways England's database (SMIS, see Section 5) and other local databases; however, these were designed with ad-hoc architecture and not-standard core structure.

4. A risk-based approach for bridge assessment

The last decades have witnessed the shift from “fighting” natural hazards to “managing” the risk from them [56]. These risk-based approaches provide a methodological framework formed by three elements: hazard, exposure and vulnerability [57]. Such methods are particularly suitable for low-probability high-impact events, such as floods [19].

All riverine bridges are subjected to the risk of flooding, as naturally located upon rivers. Different consequences arise from floods depending from the hazard intensity and the vulnerability of the bridge. The vulnerability does not come from the type of structure alone (e.g. bridge design, material), but includes a range of influential factors, such as the catchment topography or the load intensity.

It is of note that existing BMS modules differ from the “risk modules”, probably because the notion of risk is relatively recent; environmental considerations (e.g. an “environmental module”) is then missing from current management systems.

4.1. Hazard assessment

The hazard module deals with simulating a range of flooding scenarios and each event is defined by a specific Intensity Measure (IM e.g. flood depth, velocity, etc.), location and probability of occurrence based on historical data. The river flow is governed by rainfall duration and intensity, as well as by ground conditions (saturation, permeability); saturated grounds can amplify impacts, especially in the case of storm clusters. The type of drainage and the catchment topography can deeply influence the flooding impact on structures; for example, steep catchments are characterised by high velocity floods and debris, while open catchment are likely to be impacted more by inundations rather than water velocity.

The first step consists in estimating the hydrodynamic forces with hydraulic and hydrological models. Extensive literature is available regarding assumptions and characteristics of the multiple conceptual, physically-based, and stochastic hydrological models developed so far [58–61]. The second stage involves the impact modelling of the forces on the bridge, by considering the asset characteristics (exposure); this stage is illustrated in Section 4.3.

4.2. Exposure of the bridge stock

An optimal asset management starts with complete data of the assets, i.e. the exposure [25,40]. The exposure contains details of the location, value and characteristics of the “assets at risk”, i.e. bridges potentially subjected to damage or disruption. Information can be derived from geo-information systems, inspections and other available datasets; these are objective properties, independent from the hazard.

The US National Bridge Inventory (NBI, see Sec. 2) is a good example of a modern database with a standard format [62]. It is geocoded and helps governments to manage local and national bridges; for example, some US communities share information about local bridges on

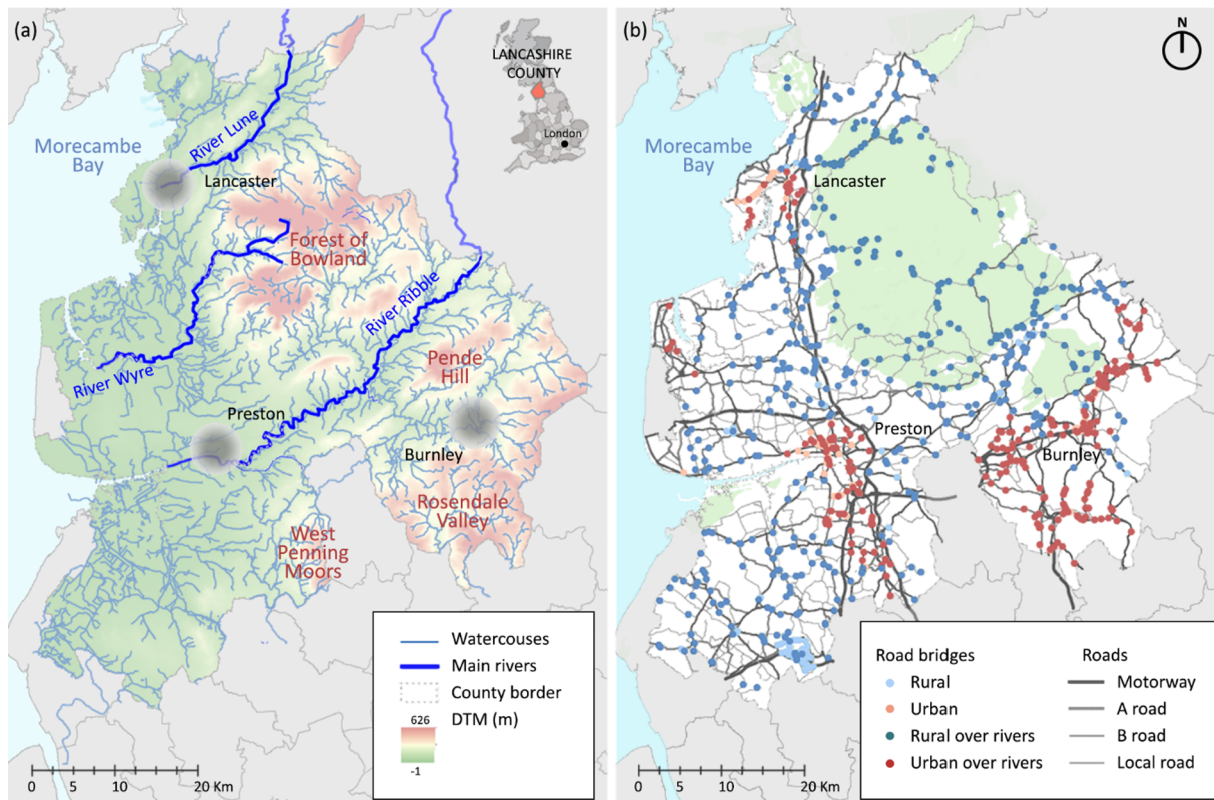


Fig. 3. An overview of the Lancashire area: (a) the county's natural features; (b) the county's road bridges (EDINA Digimap Ordnance Survey Service).

public platforms, giving the opportunity to comment and feedback. Citizens can also make decisions on this, e.g. commuters can make their own consideration about their route to work in case of a bridge disruption [63].

In England, multiple authorities are responsible for the bridge stock: (i) Network Rail, for railway bridges; (ii) Highways England, for most motorways and few A road bridges; (iii) local authorities, for few highway bridges, most A road bridges and local bridges at county level. Each authority has his own method of data collection and risk assessment; although some best-practice is shared through national forums (e.g. the Bridge Owner's Forum; the Association of Directors of Environment, Economy, Planning and Transport - ADEPT), the consistency and quality of record is not satisfying [16]. It is expected that the different datasets contain similar general data (e.g. location, road type), although no common framework exists to guarantee the interoperability of databases. Moreover, more specific information is scarce, particularly regarding foundation type, height above river and material. Well-known relations, local knowledge and expert opinion can support assumptions for covering some gaps in the datasets (for example, assuming the structure type based on material and age); however, this type of reasoning is not always reliable and generally time-consuming.

4.3. Vulnerability and damage modelling

The vulnerability is the susceptibility of exposed elements of being damaged by adverse events [57]. The damage estimation consists of evaluating costs and losses, under different load conditions of hazard. Worldwide, Damage Functions (DFs) are recognised as the standard method for urban flood assessment, and a wide range of research is present in the literature [64–68]. DFs relate hazard IMs to the damage experienced by the object at risk, representing its susceptibility to the hazardous event.

Traditionally, DFs presents the monetary damage for buildings affected by floods according on the building use and typology (e.g.

similar buildings have the same DF) [69]. Less research has been done for infrastructure; models such as HAZUS-MH computes physical damages of roads and bridges [70,71], while very limited research investigates on their functionality loss [72]. This area requires more research [73], but such development is out of the scope of this study.

Identifying bridges with the same vulnerability is functional for preventing simultaneous failures, especially during extreme events and storm clusters. The vulnerability identification usually includes the development of a ranking (risk score). This is on-going in many agencies (e.g. Network Rail, Highways England), although limited to structural properties and not-inclusive of environmental factors [14].

5. Towards a national bridge database (UK) for risk assessment

Flood risk assessment to bridges is challenging. Vulnerability and exposure are dynamic entities, depending on temporal and spatial scales, as well as on a wide range of factors (e.g. economic, social, environmental, etc.) [57]. Nevertheless, exposed elements can be detailed into inventories, which can support monitoring changes. In the UK, the method for data collection varies according to the responsible authority who manages the asset. Clear criteria for recording information are the onset for harmonising data, and produce useful inventories (e.g. that allow comparisons). A first taxonomy of bridges at flood risk is proposed in Section 5.2, as an effort to produce a protolled method for gathering or creating uniform data over the country, based on the inter-operability between the databases of different owners.

5.1. Bridge risk management in Lancashire (UK)

The Lancashire County Council (LCC, in the North West of England; 2017 population: 1,449,300; area: 3,080 km²) manages more than 1800 road bridges. Motorways and railways run from North to South as well as from East to West, therefore it can be considered a high-infrastructure area. It is in the top-three counties for both absolute number

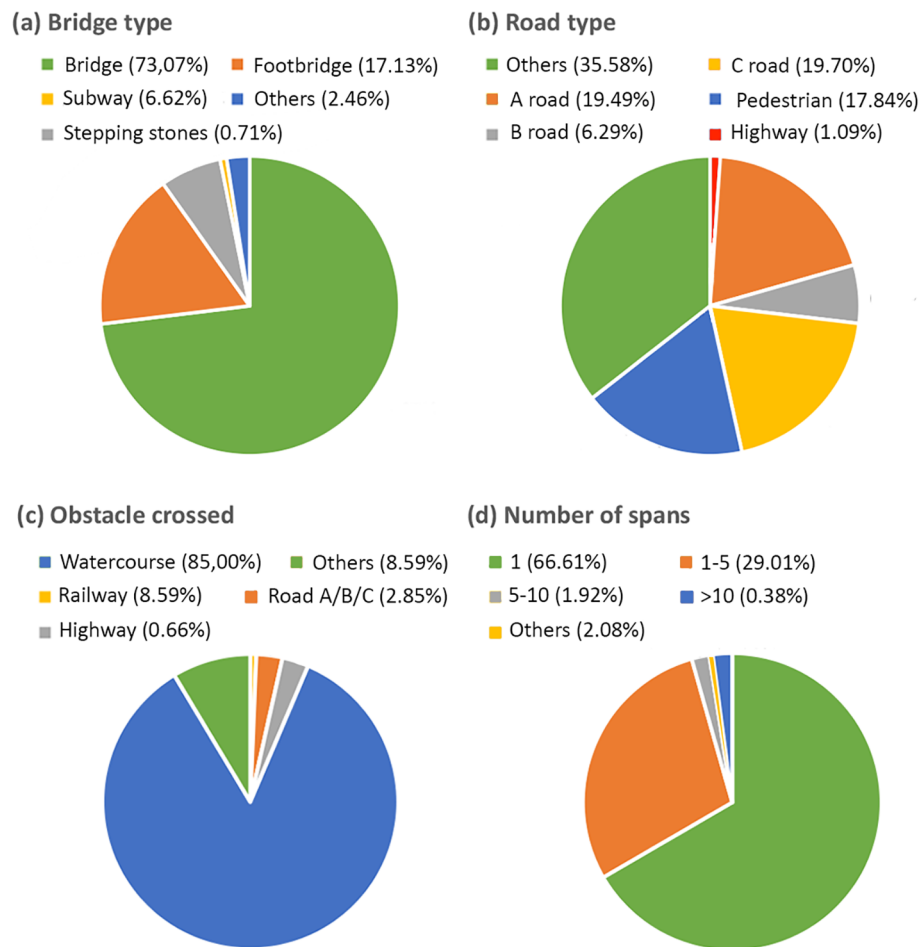


Fig. 4. Statistics from the bridge register of the Lancashire County Council (source: Lancashire County Council).

of bridges and number of bridges per m^2 (Fig. 1). Lancashire water-courses drain westwards from the Pennines into the Irish Sea, and include three major rivers (Ribble, Wyre and Lune) and their tributaries (Calder, Darwen, Douglas, Hodder, and Yarrow) (Fig. 3).

Lancashire is a flood-prone region where flooding caused by extreme rainfalls has become a bigger issue over the last few years [74]. During the 2009 floods, several major roads were flooded and not passable, and various bridges were closed due to concerns over structural integrity (while six bridges collapsed in the neighbouring Cumbria region).

These events lead to the development of a bridge protection programme. The BMS of the LCC includes a bridge register that collects information regarding the bridge geometry (length, width, number of span, bridge type), location (urban/rural), maintenance (targeted/preventive/minimum), road type, crossed obstacle, carried loads (Fig. 4).

Most of the Lancashire bridges (75%) are allowed to carry > 40 t, thus without particular load restrictions; almost all the structures (99%)

have length < 100 m. 88 structures are recognised as listed (Grade II) by Historic England, i.e. they are of special interest and must be preserved. For the 30% and 36% of their structures, targeted and preventive maintenance is respectively planned.

The LCC developed a preliminary risk rating for scour on the basis of the register, by weighting various factors with a score ranging from 5 to 30 (see Table 1). The sum of all the scores gives the risk rating for a specific bridge. All structures with a score higher than a baseline value (140) were classed as susceptible to scour; this baseline score was developed via expert opinion [75]. A desktop study in 2010 reported 56 structures at major risk, considering scour only.

Although the register is a remarkable example of local management, the LCC authorities underlined that the database includes handmade tasks (e.g. computing diversion), that are necessarily approximate. Furthermore, despite the considerable number of attributes, fundamental information for a complete flood risk assessment (such as the structural design principle, primary material, and the age of the bridge)

Table 1

The score rating system for the LCC bridge register (source: Lancashire County Council).

Road type	Diversion	Affected area	No. of spans	Total span	Foundations	Bed material	River type	Flow rates	SCORE
–	–	–	> 5	–	–	–	–	–	30
Motorway	> 25 km	City	–	> 100 m	No details	Unknown	–	–	25
A road	15–25 km	Major town	4–2	50–100 m	Spread footings < 1 m from bed level	Gravel/alluvium	Tidal main river	Fast	20
B road	10–15 km	Town	1	25–50 m	Spread footings > 1 m from bed level	Shale rock	Main river	–	15
C road	5–10 km	Village	–	10–25 m	Sheet piles	Solid invert	Non-main river	Medium	10
Unclassified	1–5 km	Hamlet	–	< 25 m	Piles	–	–	Slow	5
Footpath	–	–	–	–	–	–	–	–	3

Table 2

The proposed bridge taxonomy, considering road and rail bridges at risk of flooding.

Attribute	Description	Field(s)
1. Bridge ID	Unique code for identification of the asset	Code (alphanumeric/text/integer)
2. Bridge name	Name of the bridge from records	Name (text)
3. Location (geo-references)	Geographical position of the bridge	Easting, Northing (double)
4. Topography	Catchment	Area (m ²)
5. Peak flow rates	Speed at which water travels	Fast (< 2m/s) Medium (1–2 m/s) Slow (< 1 m/s)
6. Water depth	Changes in water level with respect to bridge deck height	(mm)
7. Age (or period)	Date in which the bridges was completed or century of realisation	Year/century (integer)
8. Bridge type	Principle of the bridge structural design	Beam Truss Arch Cantilever Suspension Cable Stayed Other (specify)
9. Material	Material used for the structure of the bridge	Masonry Concrete Steel Iron Wood Stone Other (specify)
10. Length	Bridge length	Total span length (m)
11. Width	Bridge width	Deck width (m)
12. Span	Number of span(s)	Span number (integer)
13. Span length	Length of each (i) span	i-span length (m)
14. Deck height	The height of the bridge deck	Deck height (m)
15. Foundation type	Type of foundation of the bridge	Isolated footings Strip footings Rafts Piles Piles walls Caissons Other (specify)
16. Road type	Road type carried by the bridge as classified by national standards	Motorway A road B road Local Rail Other (specify)
17. Obstacle crossed	Obstacle overcome by the bridge	Road name (text) River name (text) Rail (text) Other (specify)
18. Past incident	Recorded past events that caused problems to the bridge	True/False If True: year and type of incident (integer, text)
19. Past maintenance	Recorded past interventions of maintenance	True/False If True: year and type of intervention (integer, text)
20. Flood design	Adopted flood design or standard	Return period Other (specify)

is missing [76]. The structure of this database (e.g. attributes, labels, rating) differs from the one of Highways England or Network Rail. Finally, available flow and flood data (such as those from gauge stations) are not integrated with the bridge register information. The register is in the process to be updated, and a common core format is sought by authorities.

5.2. A protocolled taxonomy for data collection

Similarly to the SYNERG-Y work [77] for seismic risk assessment, a detailed taxonomy is advanced for bridges prone to floods. The proposed bridge taxonomy aims to be used by practitioners in the UK, where data collections is currently limited. It follows precise criteria for development: (i) be relevant and comprehensive by including the fundamental features for evaluating the bridge performance in the context of flood risk; (ii) be intuitive and user-friendly, in order to be handled by sub-contractors; (iii) be applicable to the UK context, where data

collection is currently not advanced.

The taxonomy was developed on the basis of data from literature [5,7,32,62,78], manuals (e.g. [13] and expert opinion (e.g. Highways England, Department for Transport). 20 attributes have been considered for describing the characteristics of road and rail bridges in flood prone areas; they are detailed in Table 2.

Some attributes describe general features (e.g. ID, location, age), while others refer to structural parameters (type, material) and geometry (width, length, span, height). Topography, water depth and peak flow rate relate to the environmental conditions, and give information regarding the vulnerability of the bridge to floods. The flood design standard indicates if any particular design has been considered (e.g. to withstand a 1-in-a-100-yr flood event). Past inundation and past maintenance are the attributes that keep record of the history of the bridge.

A taxonomy-based inventory allows making multiple queries and searches about the recorded bridges (for example: by year built, spans,

type of road and peak flow rates). By including environmental parameters, the inventory is suitable for risk modelling and it would enable the identification of the structures at higher risk. These analysis and results could be displayed via graphical tools (e.g. GIS) for strategically mapping and planning. Furthermore, a taxonomy-based inventory would also facilitate collaboration and growth of joint knowledge in the bridge community, allowing comparison of risks across the country. This taxonomy would guarantee the inter-operability among the datasets of the various bridge owners and facilitate the development of a national bridge inventory. Further insights and potential of a national bridge inventory are discussed in [Section 6](#).

6. Capability of a national bridge inventory

In an era of changes and austerity, bridge owners need to know the risk level of their assets in order to prioritise resources. A national bridge inventory would support identifying the structures in need of mitigation measures, thus allocating funding. If associated with flood forecasting models at national scale (e.g. [79]), the national bridge inventory could be used for probabilistic analysis, supporting the estimation of likelihood, impact and location for severe events at country-scale. If associated with water level gauges and flood forecasting models (e.g. [80]), it would be also an invaluable tool for developing early-warning systems (e.g. for precautionary closure of bridges) and directing emergency operations.

In addition to sharing best-practice and joining knowledge, analysis resulting from data would also be comparable to countries overseas (e.g. USA), for an evaluation of national standards and codes. At a later stage of its development, the national inventory should also be able to include photos, drawings, and various type of documents. Such architecture will also be fundamental for recording the Big Data and “smart information” that are going to be produced in the next decades (e.g. from monitoring sensors, laser scans). A complete bridge database is also preliminary to science and transportation progress, such as 3D mapping, BIM (Building Information Modelling), Digital Twins, and real-time monitoring.

6.1. Discussion and recommendation for policy makers and authorities

A well-developed, advanced, comprehensive database produces data that is useful for the society. The proposed taxonomy is integrating structural data of bridges exposed to flood risk with environmental parameters. Cost-benefit analyses are sensitive to the exposure (of the bridge to flood hazards); the exposure may change over the asset life time, so this approach is particularly relevant in regions affected by climatic effects. This integration aims to transfer risk principles into current bridge management, shifting the focus of the fund allocation from “defected bridges” (structurally deficient bridges) to “vulnerable bridges” (bridges at risk of flooding for a combination of hazard and structural conditions), moving towards a new generation of BMSs.

The presented taxonomy is UK-based and flood-focused, but could be adopted by other countries prone to other hazards (e.g. hurricanes). In fact, the taxonomy could be modified to accommodate local features (peculiar materials or bridge types), changes over the time, and different environmental parameters. Moreover, it could also be updated for including future bridge design criteria and materials.

UK bridges are owned by various agencies and managed with different methods; the proposed taxonomy could support datasets inter-operability (e.g. using coding to harmonise data collection), and ultimately lead to a coherent nation-wide database. The presented taxonomy is a preliminary proposal that should be refined by adopting consultation and open discussion with bridge owners and experts. This discussion would enable to design a system capable of accommodating agencies' preferences and needs.

In order to facilitate the progress towards a more protocolled data collection, bridge-related authorities (such as the Bridge Owners Forum or the National Bridges Board) should formulate and advance a national strategy for the development of policies, functional for setting the bridge national database. This would advise the Department for Transport in developing a roadmap to identify specific steps for drawing and implementing protocols of data collection and datasets compilation. This would help in aligning current manual updates, defining a common regulation for data compilation and supporting the uptake in practice. Further regulation would be needed for tackling issues over the ownership of the database, alongside its ongoing updating and maintenance. One possibility is that each agency would update and maintain their own data, following a shared architecture of rules, while the Government owns the whole database. All the agencies and governmental links should agree (or not) about the public accessibility of it.

There is no doubt that the database development represents a substantial challenge for the Government and relevant agencies, considering the high number of bridges in the UK; however, it would play a crucial role in preserving public safety in future years, alongside supporting the allocation of resources and the review of existing standards.

6.2. Future research and directions

The next stage of this research will develop a pilot version of the national bridge database, considering several counties in England. This stage will investigate the availability of data and the issue of inter-operability due to different datasets, while working closer with county agencies and stakeholders.

The pilot version of the database could be applied for: (i) risk analysis for a set of flooding scenarios, by means of damage curves; (ii) economic appraisal of bridge disruption (e.g. identifying the bridges whose failure would lead to the largest economic costs); (iii) emergency planning (e.g. identifying which bridges have to remain operational during evacuation/rescue operations).

7. Conclusion

The current unavailability of high-quality data and the consequent lack of understanding of bridge performance jeopardise bridge safety, and hinder the ability to prioritise resources. The UK, as for many other countries, should not take bridge safety for granted and should take precautionary preventative action for defining a new programme for bridges at risk of floods.

Within a risk-based approach, being aware of the exposure condition (i.e. assets state) is fundamental to control and manage local and national infrastructure threatened by natural hazards. Currently, bridges are managed by a range of authorities and their in-house systems have different degrees of sophistication and methods, preventing the possibility of drawing a clear and coherent picture across the country. There is a consensus in advancing a consistent methodology, and a formal procedure, for conforming information, aiming at better analysis and assessment. In particular, the creation of a national bridge database would enable the meaningful identification and comparison of risks to bridges across the country, building a deep knowledge of the national bridge stock.

This study presented a preliminary protocolled taxonomy for data collection of bridges, while illustrating the implication of a national bridge inventory in the UK. The national database could have the capability of being integrated with hydrological and transport models, providing advanced information for estimating failures and disruption. The paper set the scene for a unified bridge database, and advocated the engagement of national authorities for developing a roadmap of policies leading to it.

Data availability statement

The author is unable to provide access to data underpinning this study. Data was provided by Lancashire County Council under a data transfer agreement which prohibited data redistribution.

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